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A MINIATURE TACTICAL Rb FREQUENCY STANDARD

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ABSTRACT

Work on an innovative design for miniature rubidium frequency standards has reached the pre-production demonstration stage at Litton Guidance and Control Systems. Pre-production units have been built and tested under contract to the Rome Air Development Center of the U.S. Air Force Systems Command. The units, which are designed for use in tactical military applications, feature fast warm-up, low power consumption, and vibration insensitivity. The output stability under vibration is maintained without the need for external shock-mounts. The design objectives and test results are discussed.

INTRODUCTION

Reported herein are design considerations and preliminary test result of the pre-production model Tactical Rubidium Frequency Standard (TRFS) developed by the Guidance and Control Systems Division, Litton Systems, Inc., under contract with the Rome Air Development Center of the U.S. Air Force Systems Command.[1]

The TRFS must be capable of operating under severe environmental conditions, specifically extreme operating temperatures and vibrations. An innovative design of a rubidium frequency standard was necessary in order to meet these requirements and to realize small size, fast warm-up, and low power consumption. Several design features are considered unique to the Litton TRFS and are discussed briefly. The Litton TRFS development program has reached the pre-production demonstration stage, and further developmental efforts are continuing. Presented in this paper are preliminary test results available from the Litton pre-production model TRFS at the demonstration stage. The Litton TRFS is shown in Figure 1, and measures 3-1/4" W x 4-1/2" L x 3-1/4" H excluding connectors.

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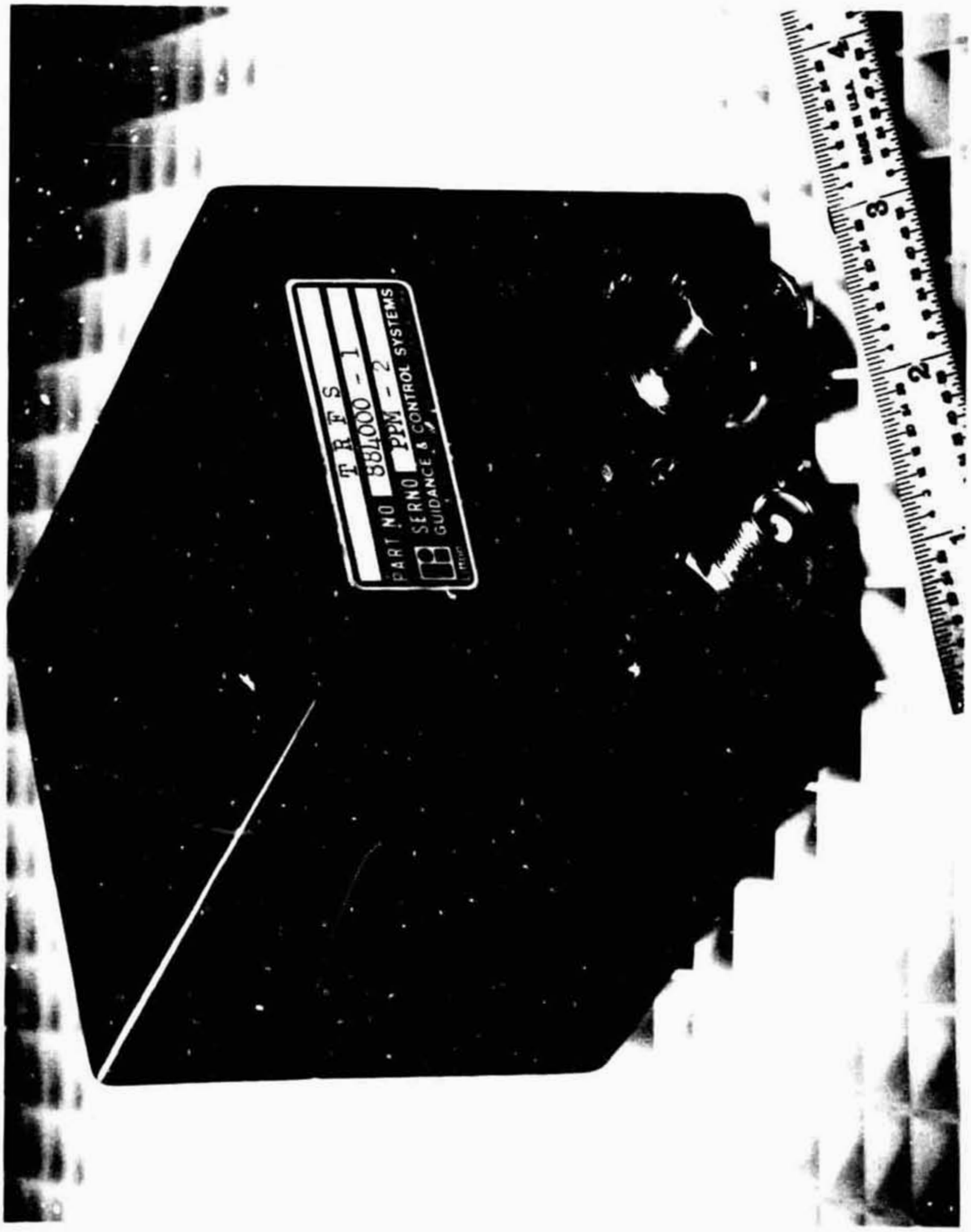

Figure 1   Litton Preproduction Model TRFS

DESIGN CONSIDERATIONS

Rubidium Physics Package

Shown in Figure 2 is the Litton TRFS physics package module. The module contains a Rb^{87} electrodeless discharge lamp and lamp driver circuitry, a 6.8 GHz microwave cavity, and a pair of coils generating a uniform magnetic field. A separate Rb^{85} filter cell and a Rb^{87} resonance cell are located inside the microwave cavity. Both cells are of cylindrical shape, 12 mm dia x 8 mm lengtn. The rubidium light from the lamp is directed through optical lenses to the filter cell, the resonance cell, and finally to the photodetector mounted on the outside of the microwave cavity.

The glass envelope of the lamp is designed to allow strong adhesion of liquid rubidium onto the glass wall, a desired feature for a lamp to be vibration resistant. The lamp driver circuitry is of the conventional type, modified for fast lamp start-up. The lamp starts within 10 sec and 30 sec at room temperature and at -55°C, respectively. Lamp start up in a "wrong discharge mode" is prevented through an electronic control under all power off-on conditions.

Both the lamp housing and the cavity are maintained at elevated temperatures by strip heaters. The strip heaters represent an extended uniform heat source, rather than a point source, and tend to reduce the temperature gradient across the heated block. Unique design of the strip heater temperature control circuitry minimizes stray magnetic fields, which would cause an excessive frequency shift when heater current changes, for example, as a function of environmental temperatures.

The microwave cavity is of rectangular shape as described previously.[2,3] The extremely small size of the cavity has resulted in rapid warm-up, as it will be shown later, with low peak warm-up power.

The entire physics elements are enclosed within two layers of magnetic shields. The outer shield, which is seen in Figure 2, measures 1-3/8" x 1-3/8" x 3". Its performance characteristics are similar to those described previously.[4]

VCXO

The VCXO is a self-contained module (1.2" x 1.2" x 2.4") complete with heaters and oscillator electronic circuitry.[5] The quartz crystal in the VCXO is a SC-cut 10 MHz crystal having an acceleration sensitivity of $\Upsilon \approx 4 \times 10^{-10}$/g. The VCXO module is mounted on a set of wire-suspended vibration isolators inside the TRFS package.

The wire-suspended isolators were chosen instead of the conventional rubber-type primarily due to their consistent

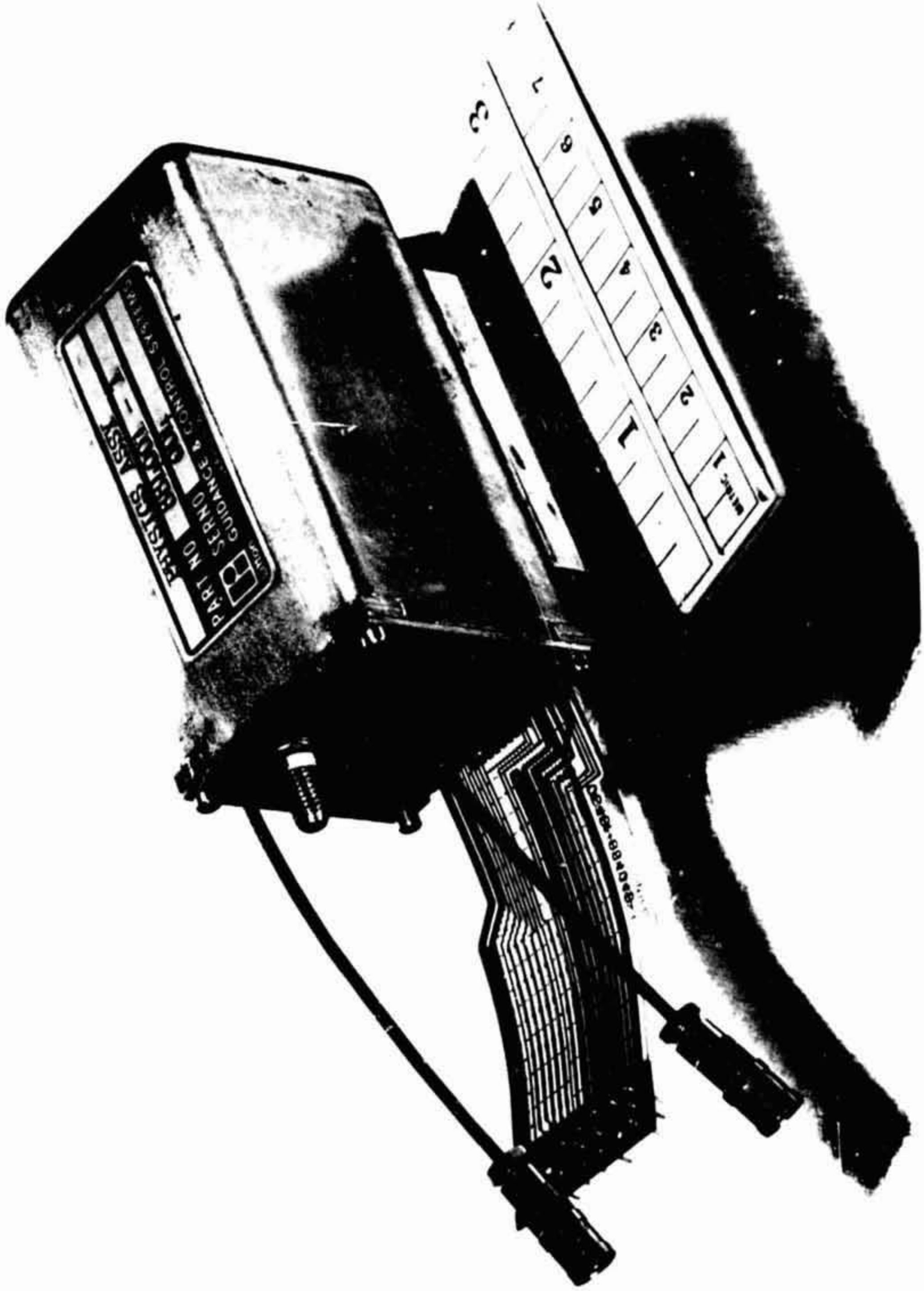

Figure 2 Physics Package Module of the Litton TRFS

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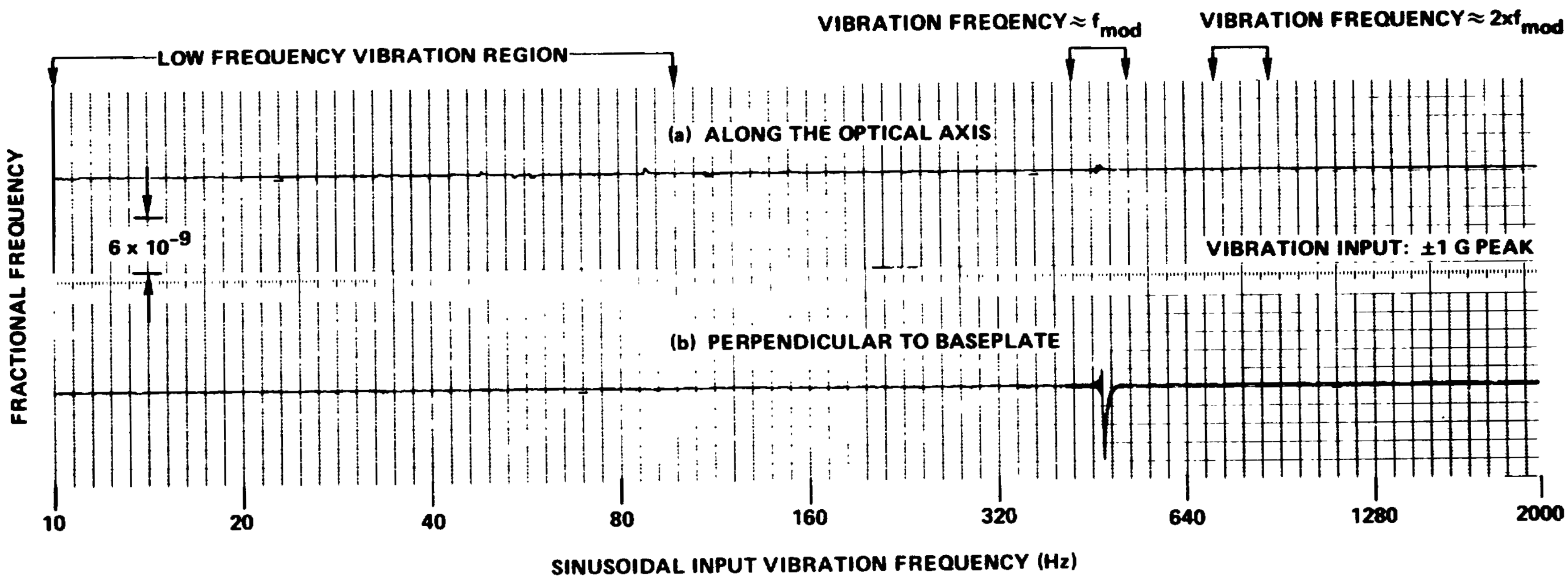

Figure 3 Fractional Frequency Shift versus Vibration Frequency for Vibration Input (a) along the Optical Axis, and (b) along the Axis Perpendicular to the Baseplate

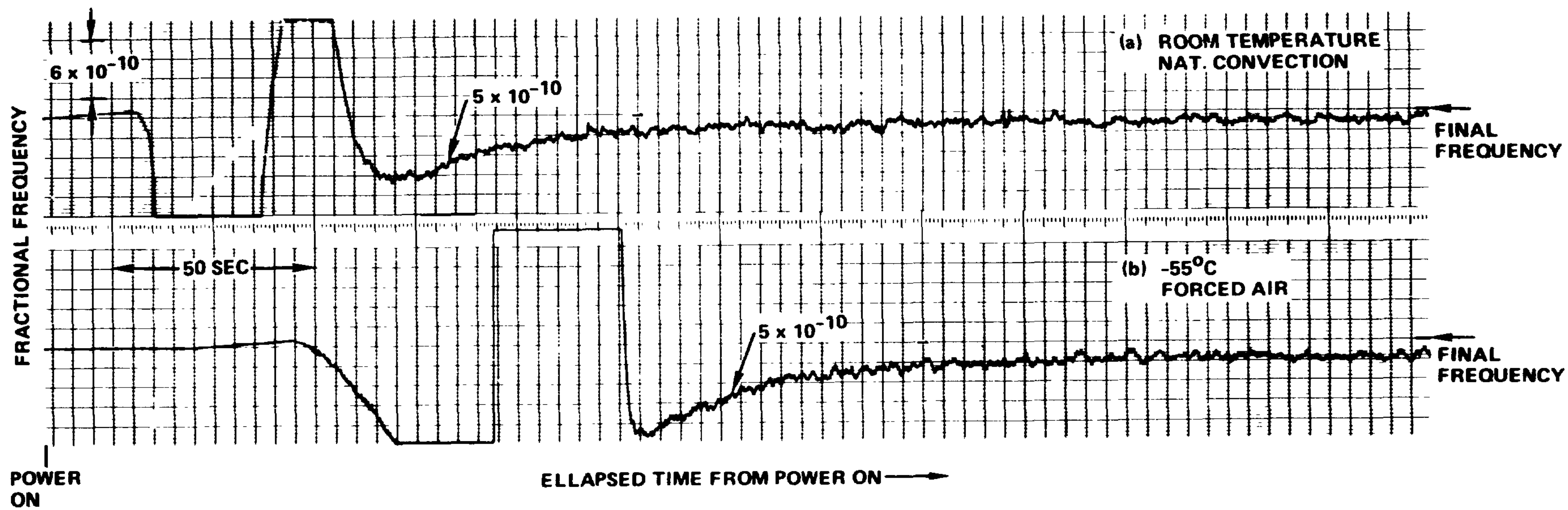

Figure 4 Fractional Frequency versus Time from Turn-on (a) at Room Temperature with Natural Convection, and (b) at -55°C with Forced Air

characteristics under all temperatures. (The rubber mounts tend to harden at low temperatures.) The isolator transmissibility is designed to have a minimal resonance rise while providing a high attenuation of vibration inputs at high frequencies.

Vibration-induced sidebands of the VCXO output, including those at the isolator resonance rise, are minimized by a fast VCXO control servo loop (bandwidth $\approx$100 Hz).[6]

Vibration Sensitivity Design Considerations

Sources of vibration sensitivity in a conventional rubidium frequency standard have shown to be both the VCXO and the physics package.[7] Since the output of a rubidium frequency standard is essentially that of a VCXO, vibration-induced sidebands of the VCXO appear directly in the frequency standard output at all vibration frequencies. In most frequency standard applications, either as a clock or as a stable, low-noise frequency source, the vibration-induced sidebands do not appear to be a serious drawback at high vibration frequencies. In order to improve the low frequency vibration sensitivity of the Litton TRFS over that of a conventional rubidium frequency standard, a large bandwidth ($\approx$100 Hz) is implemented in the VCXO control servo loop.[6]

Unlike a VCXO, the physics package is not intrinsically vibration sensitive. Vibration sensitivity of the physics package is generally considered as an engineering design challenge. In a typical mechanization of a rubidium frequency standard such as the Litton TRFS, rubidium atomic resonance signal is in the form of a modulated (ac) light intensity riding on top of a large dc light background. The ac portion of the light, i.e., the resonance signal, is an extremely small fraction of the total light intensity detected by the photodetector. The ac signal is demodulated in a conventional phase sensitive detector, and processed further to generate dc control voltage for the VCXO.

Any spurious modulation in the detected dc light intensity in addition to the resonance signal, generates an erroneous control voltage. Such an effect is most significant when the spurious modulation frequency is close to the modulation frequency (f_{mod}) of the phase sensitive detector. The spurious modulation may be a result of, for example, periodic displacement of the lamp with respect to the photodetector under vibration. The TRFS physics package is designed for maximal mechanical integrity of the whole while allowing for adequate thermal isolation of the different components operated at different temperatures.

Vibration-induced sidebands of the VCXO also cause spurious light intensity modulation. The VCXO control servo loop is upset when the vibration frequency is close to $2xf_{mod}$. In order to reduce the vibration input at this frequency, the Litton TRFS incorporates a shock-mounted VCXO.

Electrical Design

One important aspect of the electrical design is to minimize spurious signals which may upset the VCXO control servo loop resulting in an erroneous output frequency. Any spurious signal at frequencies close to f[illegible] upsets the VCXO control loop as a spurious light intensity modulation does. The interference effects observed[8] in a rubidium frequency standard operating in the vicinity of others demonstrates the effect of the spurious signal pick-up. Spurious signals may be picked up from the voltage ripple present in the input power line, if not regulated adequately.

The Litton TRFS accepts two separate power inputs: one for all heaters and the other for all electronics. Both power inputs may be 22V to 33VDC with ripples as large as 3Vrms at audio frequencies, and may contain high voltage transients.

Voltage regulation for electronics is accomplished by a switching DC/DC converter followed by a linear regulation stage. This combination provides adequate ripple regulation and constant power dissipation at all input voltage conditions. The feature of constant power dissipation minimizes input voltage dependent frequency shift (via temperature dependence of output frequency).

The 6.8 GHz resonance interrogation frequency is generated by a step recovery diode (SRD), which is driven by ~40 MHz. Direct frequency synthesis technique is used to generate 40 MHz from the VCXO 10 MHz.

The rubidium resonance signal is detected in a conventional way with sinusoidal modulation technique. The modulation waveshape is generated piecewise digitally through dividing the VCXO 10 MHz and adding the resultant square waves with proper amplitudes.

Temperature control circuitry, which maintains the lamp and the cavity at elevated temperatures, is of high gain, and utilizes both proportional and integral gain. Combination of unique circuit design and the strip heater minimize the stray magnetic field generated by heater current.

The entire circuitry is contained in five circuit cards, each having the size of ~3"x3". Each card contains more than one layer of ground plane which acts also as heat paths for electronic components. Neither hybrids nor LSI's are used in the entire design; all components are discrete devices.

All material, components, processes and construction methods are in accordance with the governing military specifications and/or with the accepted military practice.

Mechanical Design

The Litton TRFS package is designed with a modular concept: five circuit cards, EMI filter-multipin connector module, physics package, and VCXO module. One of the five circuit cards is a mother board into which all modules are plugged. No hard-wiring is necessary between the modules; miniature RF connectors are used for all coaxial cable connections.

The package bonding is per the governing military specification. The case may be sealed by laser-weld, if necessary, for water immersibility. Heat dissipation is accomplished primarily by conduction through chassis structure to the baseplate.

Vibrational characteristics of the entire structure was studied by finite element method, and was determined to be satisfactory.

PRELIMINARY TEST RESULTS

The TRFS development program has reached a demonstration stage at Litton. As a part of planned design verification tests, the TRFS unit has been subjected to a number of functional and environmental tests. Design modifications are planned if the test results warrant them. Such modifications, if necessary, are expected to be minor in nature. When completed, the TRFS unit will be subjected to rigorous military qualification testing. Discussed in this section are the test results available to date. Design verification tests are continuing.

Sinusoidal Vibration

Figure 3a and 3b are the plots of fractional frequency shift versus vibration frequency under sinusoidal vibration of ±1g peak acceleration for vibration inputs along the optical axis and along the axis perpendicular to the baseplate, respectively.

The optical axis is parallel to the baseplate. Bandwidth of the frequency measurement system including the strip-chart recorder is a few Hz, while the vibration input is swept from 10 Hz to 2KHz at a rate of one octave/min. (The horizontal axis of Figures 3a and 3b is, however, linear in time.)

Referring to Figure 3a, the observed frequency shift is less than $\pm 3 \times 10^{-10}$ from the nominal under all vibration frequencies including those of f_{mod} and at $2xf_{mod}$.

Figure 3b is for vibration input applied along the axis perpendicular to the baseplate, and shows no observable frequency shift within $\leq 2 \times 10^{-10}$ under all vibration frequencies except as noted below.

A large unexpected frequency shift was observed in Figure 3b, when vibration frequency is close to f_{mod}. Investigation revealed that a fastening screw was loose during the test causing the microwave cavity rock excessively within the physics package.

We note that no measurable frequency shift was observed at vibration frequencies close to $2xf_{mod}$, and that output frequencies are well behaved at low vibration frequencies. No loss of resonance lock were seen during the measurement.

Audio Susceptibility

Audio susceptibility refers to the TRFS output frequency dependence on the audio frequency voltage ripple present in the input power. Test was conducted with a 3Vrms ripple added to the nominal dc voltages applied to the power input for electronics. The ripple frequency was varied slowly from 5 Hz to 2K Hz dwelling for an extended period of time at ripple frequencies equal to $1/2f_{mod}$, f_{mod}, and $2f_{mod}$. No frequency shift was observed beyond the measurement precision ($\leq 2x10^{-10}$).

Warm-up and Power Consumption

Figures 4a and 4b are typical output frequency behavior during warm-up after temperature soak at room temperature (natural convection) and at -55°C (forced air), respectively. Warm-up test results are summarized in Table I.

Table I - Litton TRFS Warm-Up Characteristics

	Time After Power-On	
	Room Temp	-55°C
o Lamp Start	8 sec	28 sec
o Resonance Lock	1 min 12 sec	2 min 22 sec
o Warm-up to $5x10^{-10}$ from the final freq.	1 min 39 sec	2 min 49 sec
o Total Steady State Power	10.4 watts	19.5 watts
o Total peak power during warm-	84 watts for 20 sec	84 watts for 42 sec

Temperature

No measurable frequency shift was observed beyond the measurement precision ($\leq 2x10^{-10}$) when the TRFS was subjected to environmental temperature steps ranging from -55°C to +71°C.

Orientation

A rubidium resonance frequency may be orientation dependent under the influence of earth magnetic field. Displacement of physics elements with respect to each other under gravitation may also be a source of orientation dependency. In a properly designed physics package, both of these effects are considered to be negligible. Perhaps the most significant orientation dependence of the TRFS output frequency arises from its temperature sensitivity. This is because the rate of heat dissipation, and therefore the baseplate temperature of the TRFS, depend on the orientation. Such a temperature-related frequency shift was reported by others[9] while measuring static g-sensitivity of an oven-controlled crystal oscillator.

The TRFS unit was positioned at various orientations while its output frequency was monitored continuously. The unit was held fixed at each orientation for an extended period of time in order to observe any temperature-related frequency shift. No measurable frequency shift was observed above the measurement precision ($\leq 2x10^{-10}$).

Input Voltage Variation

Similar argument presented for the orientation dependence applies to the input voltage dependence. If a unit depends solely on a linear voltage regulator whose heat dissipation depends greatly on the input voltage level, temperature dependence of the output frequency may be manifested as if it were the voltage dependence. As discussed earlier, the Litton TRFS incorporates a switching DC/DC converter followed by a linear regulator.

The Litton unit was powered at +22 Vdc and then the input voltage was varied to 33 Vdc by steps of a few volts. At each voltage, the unit was operated for an extended period of time to observe temperature-related frequency shift. No measurable frequency shift was observed with measurement precision of $\leq 2x10^{-10}$.

Short-Term Stability

Short-term stability of $\leq 4x10^{-11}$ at 1 sec averaging time was measured with phase noise ≤-70dB/Hz at 1 Hz away from the 10 MHz carrier. Note that the measured stabilities are those of physics resonance signal, not those of VCXO. Physics stability of $\leq 2x10^{-11}$ is obtainable, if desired, with a minor modification.

SUMMARY AND ACKNOWLEDGEMENT

Design features unique to the Litton TRFS are presented briefly. Preliminary test results are reported. Demonstrated performance characteristics of the unit under vibration, excellent warm-up time and temperature sensitivity break new grounds for the rubidium frequency standard technology to be beneficial to many tactical military applications. We wish to express our appreciation for encouragements from Mr. Richmond (Dick) Terrell, Dr. Emery Moore, Mr. Harry Daubert, Mr. Alex Hertzberg, and Mr. Dave Deuser. Much of our work has received technical support from Mr. Chong C. Lee and Mr. Carl Davidson. Technical advices of Mr. Bruce Grover, Mr. Howard Williams and Mr. Jim Steele are acknowledged.

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QUESTIONS AND ANSWERS

ALAN JENDLY, OSCILLOQUARTZ: I have a question regarding the g-sensitivity, the static g-sensitivity.

MR. KWON: All right.

MR. JENDLY: You mentioned that you are using an oscillator which typically has a static g-sensitivity of four parts in ten to the minus ten per g.

MR. KWON: That's correct.

MR.JENDLY: You also mentioned that you are using it at a bandwidth of about 100 Hz, I believe. Then you say that this device, the complete device, is totally insensitive to orientation.

My question is: If you take this device and slowly rotate it by 180 degrees, and 90 degrees within the three axes, don't you measure those four parts in ten to the ten?

MR. KWON: The answer to that question is no, because we have a very fast servo loop. So, the orientation dependence of the VCXO is servoed out by the physics package.